Serial Bus Network Type Multi-Sensor Platform Based on Configurable Interface LSI

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論文内容要約

As the population ages, not only more industrial robots, but also more service robots, are needed to support our society. Since humans and robots come into physical contact under a variety of circumstances, the detection of tactile interactions between humans and robots is needed to realize a safer, more reliable and more accurate human-robot communication.

To date, two readout schemes have been mainly investigated to install tactile sensors in a robot. One scheme is to use a scanning readout circuitry, in which the digitization of sensor output is performed off the sensor array in a central processing unit. So far, some scanning-readout type sensor arrays, which can include many sensing elements based on capacitive and resistive transduction, were reported. However, with increase in the number of sensing elements and the covering area, the number and length of wires increase. The interference effects along a long signal propagation pathway, the crosstalk from element circuits and the long scanning time make this scheme difficult to scale efficiently for large-scale tactile sensor networks. Another scheme is to digitize the sensor output at the site of sensation, and build a sensor network system with serial bus communication. This scheme has advantages in reducing the amount of wiring, the interference effects and the crosstalk. However, the long sensing data conversion time of commercially available Analog-to-Digital Converter (ADC) chips limits the system performance. In addition, when many ADC chips are mounted on a shared bus line, the data collision and congestion will also be problems.

Since the target applications of our project includes the whole robot body coverage by tactile sensors, the high scalability and interference robustness of the tactile sensor system are important. Therefore, the on-site digitization scheme based on the serial bus communication was chosen. Considering the limitations of the conventional tactile sensor systems for robots, a 3-layer structure system named multi-sensor platform was proposed, and a configurable interface LSI was introduced. The multi-sensor platform includes 3 layers for separating computation load, and the asynchronous serial bus communication is used for increasing scalability. The interface LSI has the collision avoidance function for relieving data collision, and the human-inspired event-driven and adaptation functions for relieving data congestion. A high frequency (64 MHz in design) on-chip clock of the interface LSI ensures a fast sensing data conversion time. Main contents of this dissertation are to develop the multi-sensor platform based on the interface LSI. The following summarizes each chapter and gives out the corresponding conclusion.

Chapter 2 Multi-Sensor Platform Based-on Configurable Interface LSI

In this chapter, the structure of the multi-sensor platform was proposed, which consists of three layers: the interface LSI, the FPGA-based relay node and the PC-based host layers. Three types of sensors—temperature sensors, capacitive and resistive tactile sensors—can be included in the multi-sensor platform. The interface LSI can be configured by the configuration commands, and generate data packets including temperature sensing data together with capacitance or resistance sensing data. The relay node performs some primary data processing, such as data decoding and error check using Cyclic Redundancy Check (CRC) codes, for data packets received from the interface LSIs, and then transmits data packets to the PC host. The relay node also processes command packets received from the host, and then transmits the encoded command packets to the interface LSIs. The host analyzes data packets received from the interface LSIs through the relay node, and sends configuration commands to the interface LSIs through the relay node. The communication between the interface LSIs and the relay node is based on an asynchronous serial bus communication, and the communication between the relay node and the host is based on Universal Serial Bus (USB).

To test basic functions of the configurable interface LSI, an evaluation Printed Circuit Board (PCB) was fabricated, and an evaluation system including the relay node and the host was developed. The capacitance-to-digital and resistance-to-digital converters functioned well as designed. This evaluation system was used to evaluate the performance of commercially available capacitive and resistive tactile sensors. It was confirmed that the force and digital value relationship of the capacitive tactile sensor is more linear than that of the resistive tactile sensor. Adding the PDMS cover on the tactile sensor distributes the external force and leads to a more moderate relationship between external force and digital value, but causes larger hysteresis.

The evaluation PCB was also used to demonstrate the multi-sensor platform including 1 PC-host, 1 relay node, 2 interface LSIs and 9 tactile sensors (2 capacitive and 7 resistive sensors). In this demonstration, 2 interface LSIs were connected by a shared bus line, and operating in capacitive and resistive sensing modes, respectively, which showed the implementation of the multi-sensor platform with three kinds of sensors—on-chip temperature sensor, off-chip capacitive and resistive tactile sensors.

Finally, 3 FPC cables, on each of which 5 interface LSIs were mounted, were used to demonstrate the multi-sensor platform including 1 PC-host, 1 relay node, 15 interface LSIs and 12 tactile sensors (7 capacitive and 5 resistive sensors) for robot applications. In this demonstration, 15 interface LSIs were connected by a shared bus line and operating in capacitive or resistive sensing mode. The multi-sensor platform with up to 15 interface LSIs operating simultaneously on a shared bus line supporting temperature, capacitive and resistive sensing was successfully demonstrated.

Chapter 3 Multi-Sensor Platform Development and Evaluation

In this chapter, the multi-sensor platform, with 48 interface LSIs mounted on a shared bus line of 2.4 m, was developed and evaluated. A long bus line means a long delay time of the reflected signals that return from terminals. Since the interface LSI has the collision avoidance function, the bus line characteristic impedance needs to be tuned to a relatively large value to keep each interface LSI on the same bus line operating normally.

To verify the effectiveness of tuning the bus line characteristic impedance on avoiding false triggering the collision avoidance function, an evaluation PCB was designed and fabricated, on which 5 interface LSIs were mounted. The shared bus line length was designed to 1.4 m, and the bus line characteristic impedance was tuned to 112.73 Ω at 1 MHz. Through signal integrity analysis of the interface LSIs based on the measurement and simulation results, the bus signal sent by each LSI rises and falls through the corresponding threshold values of the Input/Output (I/O) cell of the LSI shortly, which do not trigger the collision avoidance function, and all of the LSIs operated normally with allowing some impedance mismatches between the interconnection and termination. The effectiveness of tuning the bus characteristic impedance was confirmed, and the simulation and measurement results agreed well.

To develop the multi-sensor platform with 48 interface LSIs, the same simulation software was used to analyze the signal integrity of the interface LSIs, and the bus line characteristic impedance was tuned to 127.6 Ω at 1 MHz. The multi-sensor platform was based on PCB, and 48 interface LSIs were implemented on a shared 2.4 m long bus line. Since the simulation and measurement results of the signal integrity analysis also agreed well, the high precision of the simulation software for a large scale multi-sensor platform which includes 48 interface LSIs was confirmed.

Then, based on the developed multi-sensor platform with 48 interface LSIs, its serial communication performance was evaluated, when 48 interface LSIs operated simultaneously with the adaptation function. In the evaluation, except for ID number, the configuration of all interface LSIs was the same, in which the data transmission speed was set to 1 MHz. For all interface LSIs, the number of received data packets per 30 s was between 1890 and 2315. For each interface LSI, the difference in the number of received CRC correct data packets among different times of data receiving was less than 12.76%. The number of data packets received from each interface LSI per 30 s was almost identical, and no obvious changing trend of the number of received data packets per 30 s along with elapsed time was observed, which show the Carrier Sense Multiple Access in addition of Collision Avoidance (CSMA/CA) was working as designed and the multi-sensor platform operated stably. The average sampling frequency of 384 capacitance channels (8 for each interface LSI) was 73.66 Hz.

After evaluating the case in which 48 interface LSIs are stimulated simultaneously, the relationship between the number of stimulated LSIs connected by a shared bus and the average sampling frequency of these stimulated LSIs was investigated. With the decrease in the number of stimulated LSIs, the average sampling frequency becomes higher under the same configuration, which shows the flexibility of the multi-sensor platform in different LSI stimulation situations. The reaction time of a single interface LSI, and the response time when 8 interface LSIs were stimulated simultaneously were also investigated. The reaction time of a single interface LSI from stimulation to starting sending a data packet was around 233.5 μs. When 8 interface LSIs were stimulated simultaneously, all 8 LSIs responded at least once within the first 17 data packets, confirming that CSMA/CA was working correctly. The best, average and worst initial response times are 350 μs, 612 μs and 955 μs, respectively.

Finally, 1 discrete capacitive tactile sensor was connected to each interface LSI in the multi-sensor platform with 48 interface LSIs. By setting the threshold values of the capacitance channels for these 48 interface LSIs, the multi-sensor platform including 48 interface LSIs with the event-driven and adaptation functions was successfully demonstrated.

Chapter 4 Second Generation Configurable Interface LSI

In this chapter, the motivation to develop the 2nd generation interface LSI and its several features were explained. In comparison with the 1st generation interface LSI, the Variable Gain Amplifier (VGA) was used to receive voltage sensing signal for resistive sensors or other kinds of sensors based on voltage sensing principle, instead of resistive sensor readout circuits. A 12-bit voltage-to-digital converter was used instead of the 10-bit voltage-to-digital converter to increase the resolution. The serial communication method was changed from single-ended signaling to differential signaling which has a better anti-interference ability. Pulse Width Modulation (PWM) outputs were added for controlling haptic drivers.

An evaluation system was developed to test the basic functions of the 2nd generation interface LSI, and evaluate the serial communication performance when several interface LSIs operated simultaneously. This evaluation system was based on a PCB, and included 1 PC host, 1 FPGA-based relay node and 8 interface LSIs which were mounted on a shared differential bus line of 80 cm.

Using this evaluation system, an experiment was performed for 3 days to evaluate the serial communication performance when eight 2nd generation interface LSIs operated simultaneously. In this evaluation, all interface LSIs were configured to operate in capacitive sensing mode with the data transmission speed being 1 MHz. During these 3 days, each interface LSI in the evaluation system operated normally, and almost even number (largest difference is 0.91%) of correct data packets were received from each interface LSI with low error rate (less than 0.008%), which is a big step for further robot applications.

In the conventional tactile sensor network system, the scanning of a sensor array or the access to ADC-based sensor nodes is centrally controlled by a host through multiplexers, synchronous clock, commands, enable signals, etc. Therefore, the behavior of the system is highly predictable. By contrast, in the multi-sensor platform developed in this dissertation, the host sends commands to each interface LSI for configuring function parameters. When the multi-sensor platform starts operating, no control of the interface LSIs is needed from the host. Each interface LSI is autonomous to some extent, and decides when to wait, when to start and stop sending data packets, according to the bus state and its inner function status. Since many interface LSIs interact with each other through the shared bus line, the behavior of a specific interface LSI is difficult to predict, but can be analyzed statistically. In comparison with the conventional system, the host loses some control of the system, but the system obtains high flexibility and adaptability.